Superconducting Microwave Cavity Made of Bulk MgB_2

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Abstract. We report the successful manufacture and characterization of a microwave resonant cylindrical cavity made of bulk MgB_2 superconductor ($T_c \approx 38.5$ K), which has been produced by the Reactive Liquid Mg Infiltration technique. The quality factor of the cavity for the TE_{011} mode, resonating at 9.79 GHz, has been measured as a function of the temperature. At $T = 4.2$ K, the unloaded quality factor is $\approx 2.2 \times 10^5$; it remains of the order of $\times 10^5$ up to $T \sim 30$ K. We discuss the potential performance improvements of microwave cavities built from bulk MgB_2 materials produced by reactive liquid Mg infiltration.

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The very low surface resistance of superconducting materials makes them particularly suitable for designing high-performance microwave (mw) devices, with considerably reduced sizes. The advent of high-temperature superconductors (HTS) further improved the expectancy for such applications, offering a potential reduction of the cryogenic-refrigeration limit, with respect to low-temperature superconductors. A comprehensive review on the mw device applications of HTS was given by Lancaster [1]. Among the various devices, the superconducting resonant cavity is one of the most important applications in the systems requiring high selectivity in the signal frequency, such as filters for communication systems [2], particle accelerators [3, 4], equipments for material characterization at mw frequencies [1, 5].

Nowadays, one of the commercial applications of HTS electronic devices are planar-microstrip filters for transmission line, based on $YBa_2Cu_3O_7$ thin or thick films [1, 6], whose manufacturing process allows having an high degree of device miniaturization. Nevertheless, the need of high performance, in many cases, overcomes the drawback of the device sizes, as, e.g., in the satellite-transmission systems, radars, particle accelerators, and demands for cavities with the highest quality factors. Since the discovery of HTS, several attempts have been done to manufacture mw cavities made of these materials in bulk form [2, 7, 8]; however, limitations in the performance were encountered. Firstly, because of the small coherence length of HTS, grain boundaries in these materials are weakly coupled giving rise to reduction of the critical current and/or nonlinear effects [9], which worsen the device performance; furthermore, the process necessary to obtain bulk HTS in a performing textured form is very elaborated. For these reasons, in several applications, such as particle accelerators and equipments for mw characterization of materials, most of the superconducting cavities are still manufactured by Nb, requiring liquid helium as refrigerator.

Since the discovery of superconductivity at 39 K in MgB_2 [10], several authors have indicated this material as promising for technological applications [4, 11, 12]. Indeed, it has been shown that bulk MgB_2, contrary to oxide HTS, can be used in the polycrystalline form without a significant degradation of its critical current [11, 12, 13]. This property has been ascribed to the large coherence length, which makes the material less susceptible to structural defects like grain boundaries. Actually, it has been shown that in MgB_2 only a small amount of grain boundaries act as weak links [14, 15, 16, 17]. Furthermore, MgB_2 can be processed very easily as high-density bulk material [18], showing very high mechanical strength. Due to these amazing properties, MgB_2 has been recommended for manufacturing mw cavities [4, 19], and investigation is carried out to test the potential of different MgB_2 materials for this purpose. However, papers discussing the realization and/or characterization of mw cavities made of MgB_2 have not yet been reported.

Recently, we have investigated the mw response of MgB_2 samples prepared by different methods, in the linear and nonlinear regimes [17, 20]. Our results have shown that the residual surface resistance strongly depends on the preparation technique and the purity and/or morphology of the components used in the synthesis process. In

particular, the investigation of small plate-like samples of MgB_2 prepared by Reactive Liquid Mg Infiltration (RLI) process, has highlighted a weak nonlinear response, as well as relatively small values of the residual surface resistance. Furthermore, bulk samples produced by RLI maintain the surface staining unchanged for years, without controlled-atmosphere protection. This worthwhile property is most likely related to the high density, and consequently high grain connectivity, achieved with the RLI process, as well as to the small and controlled amount of impurity phases [21]. On the contrary, samples prepared by other techniques, though exhibiting lower values of the residual surface resistance, need to be kept in protected atmosphere to avoid their degradation. These interesting results have driven us to build a mw resonant cavity using MgB_2 produced by the RLI process. In this work, we discuss the properties of the first mw resonant cavity made of bulk MgB_2.

As the first attempt to apply the MgB_2 to the cavity-filter technology, we have manufactured a simple cylindrical cavity and have investigated its microwave response in a wide range of temperatures. All the parts of the cavity, cylinder and lids, are made of bulk MgB_2 with $T_c \approx 38.5$ K and density ≈ 2.33 g/cm^3. The MgB_2 material has been produced by the RLI process [18, 22], which consists in the reaction of B powder and pure liquid Mg inside a sealed stainless steel container. In particular, the present cylindrical cavity (inner diameter 40 mm, outer diameter 48 mm, height 42.5 mm) was cut by electroerosion from a thicker bulk MgB_2 cylinder prepared as described in Sec. 4.3 of Ref. [22], internally polished up to a surface roughness of about 300 nm. A photograph of the parts, cylinder and lids, composing the superconducting cavity is shown in Fig. 1.

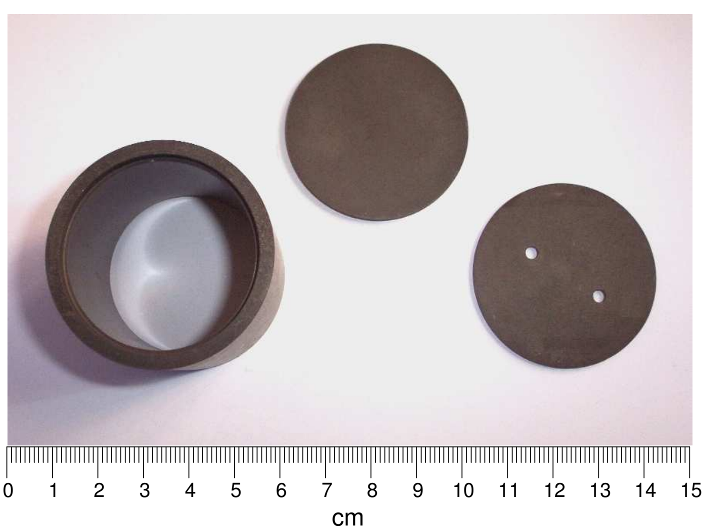

Figure 1. Photograph of the cylinder and the lids composing the bulk MgB_2 cavity. The holes in one of the lids are used to insert the coupling loops.

As it is well known, resonant cylindrical cavities support both TE and TM modes.

In the TE_{01n} modes, the wall currents are purely circumferential and no currents flow between the lids and the cylinder, requiring no electrical contact between them; for this reason, the TE_{01n} are the most extensively used modes. The TE_{01n} modes are degenerate in frequency with the TM_{11n} modes and this should be avoided to have a well defined field configuration. In order to remove the degeneracy, we have incorporated a "mode trap" in the form of circular grooves (1 mm thick, 2 mm wide) on the inside of the cylinder at the outer edges. This shifts the resonant frequency of the TM_{11n} modes downwards, leaving the TE_{01n} modes nearly unperturbed.

Two small loop antennas, inserted into the cavity through one of the lids, couple the cavity with the excitation and detection lines. The loop antenna was constructed on the end of the lines, soldering the central conductor to the outer shielding of the semirigid cables.

The ratio between the energy stored in the cavity and the energy dissipated determines the quality factor, Q, of the resonant cavity. When the cavity is coupled to an external circuit, besides the power losses associated with the conduction currents in the cavity walls, additional losses out of the coupling ports occur. The overall or loaded Q (denoted by Q^L) can be defined by

$$\frac{1}{Q^L} = \frac{1}{Q^U} + \frac{1}{Q^R}\,, \tag{1}$$

where Q^U is the so-called unloaded Q, determined by the cavity-wall losses and Q^R is due to the effective losses through the external coupling network.

The resonant frequency and unloaded quality factor of a cylindrical cavity resonating in the TE_{01n} mode are given by [1, 8]

$$f_{01n} = \frac{1}{2\pi\sqrt{\epsilon\mu}}\sqrt{\left(\frac{n\pi}{d}\right)^2 + \left(\frac{z_{01}}{a}\right)^2}\,, \tag{2}$$

$$Q^U_{01n} = \frac{1}{R_s}\sqrt{\frac{\mu}{\epsilon}}\frac{[(z_{01}d)^2 + (n\pi a)^2]^{3/2}}{2z_{01}^2 d^3 + 4n^2\pi^2 a^3}\,, \tag{3}$$

where μ and ϵ are the permeability and dielectric constant of the medium filling the cavity; a and d are the radius and length of the cavity; R_s is the surface resistance of the material from which the cavity is built; $z_{01} = 3.83170$ is the first zero of the derivative of the zero-order Bessel function.

Q^U can be determined by taking into account the coupling coefficients, β_1 and β_2 for both the coupling lines; these coefficients can be calculated by directly measuring the reflected power at each line, as described in Ref. [1], Chap. IV. Thus, Q^U can be calculated as

$$Q^U = (1 + \beta_1 + \beta_2)Q^L\,. \tag{4}$$

The frequency response of the cavity has been measured in the range of frequencies $8 \div 13$ GHz by an *hp*-8719D Network Analyzer. Transmission by two probes has been successfully used for measuring the loaded quality factor in a wide range of temperatures. Among the various modes detected, two of them have shown the highest quality factors;

at room temperature and with the cavity filled by helium gas, the resonant frequencies of these modes are 9.79 GHz and 11.54 GHz; according to Eq. (2), they correspond to the TE_{011} and TE_{012} modes. The coupling coefficients β_1 and β_2 have been measured as a function of the temperature; they result ≈ 0.2 at $T = 4.2$ K and reduce to ≈ 0.05 when the superconductor goes to the normal state. At $T = 4.2$ K (without liquid helium inside the cavity) the unloaded quality factors, determined by using Eq. (4), are $Q^U_{011} \approx 220000$ and $Q^U_{012} \approx 190000$; both decrease by a factor ≈ 20 when the material goes to the normal state.

Fig. 2 shows the temperature dependence of the measured (loaded) and the calculated (unloaded) Q values for the TE_{011} mode, Q^L_{011} and Q^U_{011}; in the same plot (right scale) it is shown the mw surface resistance deduced from Q^U_{011} using Eq. (3). As one can note, the quality factor maintains values of the order of 10^5 up to $T \approx 30$ K and reduces by a factor ≈ 20 at $T = T_c$.

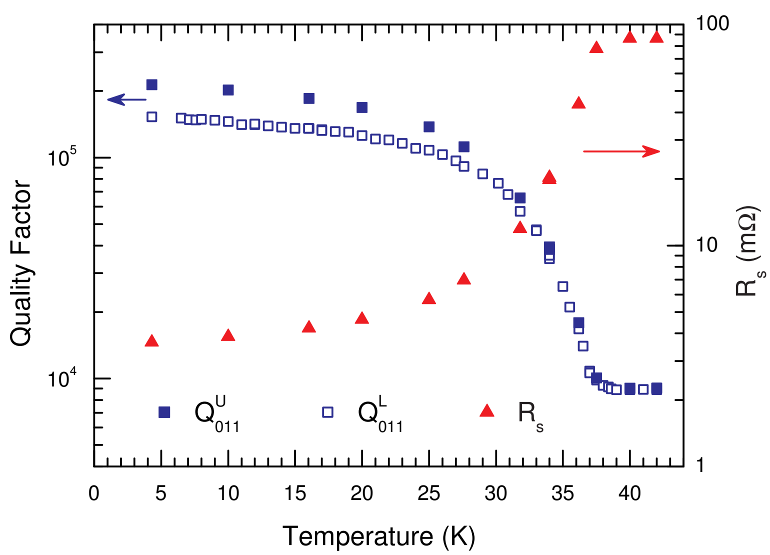

Figure 2. Temperature dependence of the loaded and unloaded quality factor, Q^L_{011} and Q^U_{011}, (left scale); mw surface resistance R_s deduced from Q^U_{011} (right scale).

The results of Fig. 2 have been obtained at low input power level (≈ -15 dBm). In order to reveal possible nonlinear effects, we have investigated the TE_{011} resonant curve at higher power levels. In this case, to avoid possible heating effects, the measurements have been performed with the cavity immersed into liquid helium. At input power level of ≈ 15 dBm, we have observed that the quality factor reduces by about 10%, indicating that, at these input power levels, nonlinear effects on the surface resistance are weak.

Our results show that MgB_2 produced by RLI is a very promising material for building mw resonant cavities. We have obtained a quality factor higher than those reported in the literature for mw cylindrical cavities manufactured by HTS, both bulk and films [2, 6, 7, 8]. Moreover, Q takes on values of the order of 10^5 from $T = 4.2$ K up to $T \approx 30$ K, temperature easily reachable by modern closed-cycle cryocoolers.

We would remark that this is the first attempt to realize a superconducting cavity made of bulk MgB_2; we expect that the performance would improve if the cavity were manufactured with material produced by liquid Mg infiltration in micrometric B powder. The present cavity is made of MgB_2 material obtained using crystalline B powder with grain mean size ≈ 100 μm. On the other hand, previous studies have shown that the grain size of the B powder, used in the RLI process, affects the morphology [23] and the superconducting characteristics [20, 23] of the material, including the mw properties.

Investigation of the microwave response of bulk MgB_2 obtained by the RLI method has been performed in the linear and nonlinear regimes [20, 17]. In the linear regime, we have measured the temperature dependence of the mw surface impedance [20] at 9.4 GHz; the results have shown that the sample obtained using microcrystalline B powder (≈ 1 μm in size) exhibits smaller residual surface resistance (< 0.5 mΩ) than those measured in samples prepared by crystalline B powder with larger grain sizes [20]. Since the residual surface resistance obtained from the Q_{011}^U data is $R_s(4.2\text{ K}) \approx 3.5$ mΩ, we infer that by using microcrystalline B powder in the RLI process the Q factor could increase by one order of magnitude.

In the nonlinear regime (input peak power ~ 30 dBm), we have investigated the power radiated at the second-harmonic frequency of the driving field [17]. Since it has been widely shown that the second-harmonic emission by superconductors at low temperatures is due to nonlinear processes in weak links [9, 25, 26], these studies allow to check the presence of weak links in the samples. Our results have shown that MgB_2 samples produced by RLI exhibit very weak second-harmonic emission at low temperatures. In particular, the sample obtained using microcrystalline B powder does not show detectable second-harmonic signal in a wide range of temperatures, from $T = 4.2$ K up to $T \approx 35$ K [17]. So, we infer that eventual nonlinear effects in the cavity response can be reduced by using microcrystalline B powder.

Because of the shorter percolation length of the liquid Mg into very fine B powder (1 μm in size), the production of massive MgB_2 samples by RLI using microcrystalline B powder turns out to be more elaborated. In this work, we have devoted the attention to explore the potential of bulk MgB_2 materials prepared by RLI for manufacturing mw resonant cavities; work is in progress to improve the preparation process in order to manufacture large specimens using microcrystalline B powder.

In summary, we have successfully built and characterized a mw resonant cavity made of bulk MgB_2. We have measured the quality factor of the cavity for the TE_{011} mode as a function of the temperature, from $T = 4.2$ K up to $T \approx 45$ K. At $T = 4.2$ K, the unloaded quality factor is $Q_{011}^U \approx 2.2 \times 10^5$; it maintains values of the order of 10^5 up to $T \sim 30$ K and reduces by a factor ≈ 20 when the superconductor goes to the normal state. To our knowledge, these Q values are larger than those obtained in HTS bulk cavities in the same temperature range. The results show that the RLI process provides a useful method for designing high-performance mw cavities, which may have large scale application. We have also indicated a way to further improve the MgB_2 mw cavity technology.

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